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Accelerator Technology For Bright Radiation Beam*

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Abstract

We review the current and future accelerator technologies for generation of high brightness radiation beam.

1. Introduction

The most promising way known at present time to generate intense, bright radiation in short wavelength range is to pass relativistic electron beams through periodic magnetic structure called undulator. The spontaneous radiation from the periodic transverse acceleration in undulator is referred to as the undulator radiation. The high brightness of the undulator radiation is the main reason why several "third generation" synchrotron radiation facilities are being built around the world. Free electron lasers (FELs), which can be regarded as a further development of the undulator radiation, will produce fully coherent, intense, tunable radiation both in the infrared and in the ultraviolet and shorter wave length regions. An optimum operation of these radiation devices requires that certain conditions on the quality of the electron beam are satisfied. Here we review those conditions and the current and future accelerator technology that will provide electron beams of requisite quality.

2. Electron beam qualities for Undulators and Free Electron Lasers

Beam quality is mainly described by three quantities: beam current, energy spread and emittance. The emittance is a measure of transverse spread and is given by the area of the transverse phase space occupied by the electron beam. The current divided by the emittance is known as the brightness.

The requirement on emittance is that it be less than about λ, the wavelength of the radiation. To be quantitative, we introduce the rms emittance as follows:

$$\varepsilon_x^o = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x \cdot x'\rangle^2} \tag{1}$$

where x and x' are the transverse position and angle, respectively, and the brackets denote the operation of taking the ensemble average. The emittance defined in the above is sometimes referred to as the "unnormalized" emittance, since it is not invariant under adiabatic acceleration. It is also convenient to introduce the normalized emittance ε_x as follows:

$$\varepsilon_x = \gamma\, \varepsilon_x^o \quad , \tag{2}$$

where $\gamma = E/mc^2$, E = electron energy, m = electron mass, c = speed of light. The normalized emittance is invariant under adiabatic acceleration as well as under beam transport consisting of linear focussing elements and drifts.

We can also associate phase space with a radiation field, and calculate its emittance [1]. The radiation emittance ε_R is minimum for the Gaussian TEM_{00} mode with the value

$$\varepsilon_R = \lambda/4\pi \tag{3}$$

To generate a transversely coherent radiation beam, it is clearly necessary that the electron beam emittance be smaller than the radiation emittance,i.e.,

$$\varepsilon_x^o \lesssim \frac{\lambda}{4\pi} \tag{4}$$

The transverse coherence is a necessary condition for FEL operation. For undulator radiation, the condition is desirable for high brightness. As an example, consider an FEL at "water window", $\lambda = 30$ Å. With a 1 GeV electron beam, the required normalized emittance is

$$\varepsilon_x \lesssim 0.5 \text{ mm-mrad} \tag{5}$$

The requirement on the relative energy spread for undulator radiation and FELs is that it be smaller than the typical bandwidth of the radiation process, i.e.,

$$\frac{\Delta\gamma}{\gamma} \lesssim \frac{1}{2N} \tag{6}$$

where N is the number of undulator periods. Typically this requirement leads to the condition that the relative beam energy spread $\Delta\gamma/\gamma$ be less than 0.1%.

The required current is typically several hundred Amperes.

The discussion in the above applies to undulator radiation and low gain FELs. For high gain FELs in the exponential gain regime [2], the emittance restriction Eq. (4) remains basically the same but N in Eq. (6) should be interpreted as the number of periods in one gain length. Rigorous discussion of beam quality effect in the high gain regime was discussed recently based on detailed FEL theory [3], [4].

3. Accelerator technology

Different considerations are applicable for storage rings and linacs as a source of bright electron beams. In the following, we consider them in turn.

3.1 Storage rings

Electron storage rings are promising as a source of bright electron beams because the unique damping mechanism improves and maintains the beam qualities in these machines [5].

In an ideal storage ring consisting of M achromatic bends, the minimum achievable emittance is

$$\varepsilon_x^0 = \left(7.7 \times 10^{-13} \text{ m-rad}\right) \frac{\gamma^2}{M^2} \tag{7}$$

This equation implies that storage rings for low emittance must have large M and thus are big: typical storage rings for state-of-the-art light source have a circumference on the order of a few hundred meters and larger.

There are several instabilities in storage rings that limit the beam quality [6]. Among these, the most significant for the present discussion is the so-called microwave instability [7], as a result of which the achievable peak current I is limited by the energy spread as follows:

$$I \leq 2\pi\alpha \frac{E}{e} \frac{1}{Z_n/n} \left(\frac{\Delta\gamma}{\gamma}\right)^2 \tag{8}$$

where e is the electron charge, Z_n/n, known as the broad band impedance, characterizes the interaction of the beam with the vacuum chamber environment, and α is a quantity known as the momentum compaction which is the coefficient relating the change in the orbit frequency to the change in momentum. For a large I, it is desirable to minimize the impedance and maximize α. For modern storage rings, the achievable value of Z_n/n is limited to about 1 Ohms. On the other hand,the momentum compaction is proportional to $1/M^2$, and therefore cannot be arbitrarily increased without compromising the emittance requirement because of Eq. (7).

The accelerator community has gained considerable experience recently in the arts of building high brightness electron storage rings in connection with the synchrotron radiation facility construction projects at several places around the world. The unnormalized beam emittance and the energy spread in these storage rings is typically about 10^{-8} mm-mrad and 0.1%, respectively. Undulators placed in the straight sections of these machines produce tunable, high brightness, short wavelength radiation beam that cannot be obtained by any other method. The performance of such devices are summarized in Fig. 1.

An interesting idea to obtain a higher peak current in a storage ring is to design the lattice so that the momentum compaction vanishes, i.e., the concept of the isochronous storage ring [8], [9]. In such a ring, the microwave instability develops so slowly that it becomes irrelevant. A more detailed analytical can experimental investigation is necessary to understand the stability of the isochronous ring.

3.2 RF Linacs

In RF linacs, it is necessary to start out with a good emittance beam, since there is no damping mechanism. The most commonly used electron source is the thermionic gun based on emission from heated cathode surface. Although electron beam from thermionic guns have a low emittance (the normalized rms emittance is less than 1 mm-mrad) the current is rather modest, being about one Amperes. In order to obtain several hundred Amperes, it is therefore necessary to bunch the long pulses from the gun to shorter pulses of higher current. This "bunching" process involves nonlinear mixing in phase space, causing a significant emittance degradation. Thus, the emittance the 10 nC pulse for the SLC gun after bunching is about 300 mm-mrad [10]. Another example is the emittance of the 1 nC, 10 psec pulse for the ALS injector, which is about 30 mm-mrad [11].

Brighter beams appear to be possible with the recent development of the laser driven RF guns[12]. In this gun, a photo-emissive surface, the photo-cathode, is placed in an RF cavity and is illuminated by intense laser beams to knock out the electrons from the surface. The advantage over the thermionic gun is that the current from photo-cathode is high so that bunching is not necessary. The time structure of the electron beam is controlled by that of the laser beam, and can be tailored to match to the requirements of the RF accelerating sections.

The emittance of RF photo-cathode gun is larger than the intrinsic emittance of the photo-emission process due to the time variation of the RF field and due to the action of the space charge force while the beam is accelerated to a relativistic energy [13]. Of these, the latter effect is usually the more important and gives rise to the following emittance:

$$\varepsilon_x^{sc} = \frac{\pi}{4}\left(\frac{2mc^2}{E_{acc}}\right)\frac{I}{I_A}\frac{1}{(3\sigma_x/\sigma_z+5)} \tag{9}$$

where E_{acc} is the peak electric field of acceleration, I_A=17,000 A is the Alfven current, σ_x and σ_z is respectively the rms value of the transverse and the longitudinal beam sizes.

With the parameters of the BNL photo-cathode gun [14], Eq. (9) gives ε_x=4 mm-mrad, which , although smaller by an order of magnitude than that produced by thermionic guns, is still an order of magnitude larger than that required for an FEL at water window, Eq. (5). It is possible to improve the emittance of the RF photo-cathode further by correcting the correlated part of the emittance growth [15],[16]. However, it would be difficult to obtain emittance values much smaller than 1 mm-mrad required for x-ray FELs. A possible way to over come this impasse is to introduce a correlation between the transverse distribution and energy spread by means of TM_{210} mode of microwave cavities [17]. Such a "beam conditioning" will effectively remove the emittance restriction, Eq. (4).

The RF cavities for acceleration can be either of the room temperature type or of the superconducting type. The room temperature cavities must necessarily operated in a pulsed mode because of the large Ohmic loss at copper surfaces. On the other hand, the RF loss in superconducting cavities is negligible. Thus linacs using superconducting cavities can be operated in a CW mode, thus producing a very high average electron beam power and hence the radiation power. Another significant advantage of the CW operation is the possibility that various beam fluctuations can be controlled to a much lower level than is feasible in room temperature linacs. In addition, the RF frequency and cavity shape can also be optimized with the view to minimize the electron beam instabilities. The development of superconducting RF cavity technology benefits from nuclear physics projects and high energy physics collider projects.

4. Prospects for the future development in FELs

Although spontaneous radiation from undulators in storage rings provide intense radiation with some degree of coherence in hitherto inaccessible wavelength regions, it is the FEL technology that offers the opportunity for generation of truly coherent radiation. The FEL development in the future needs to be pursued in two separate directions. In the infrared region, where the technology for the accelerator and the optical cavities are available, the challenge is to construct user facilities. In the short wavelength region, the challenge is to develop the technology. The electromagnetic spectrum and the projected FEL capability is shown and compared with other sources in Fig. 2.

Infrared FELs have been built and operated, but these first devices were oriented toward learning about FELs rather than toward serving a community of users. The task in the future is to build an FEL that satisfies a unique set of criteria required for a user facility. An important such criterion is the stability of the FEL output,in wavelength, in intensity and in direction. Thus the choice of the accelerator system and design must be made with the view of ensuring the required stability. As an example, the IR FEL for the Combustion Dynamic Facility [18] is based on a 500 MHz superconducting RF accelerator with the fluctuation in the electron beam energy reduced to less than 0.01 %. Another important criterion is the ease of wavelength coverage and tuning. For this purpose, the FEL optical system that includes the optical cavity, outcoupling, and the optical transport must be properly designed.

The short wavelength record in FEL is 2400 Å obtained at Novosibirsk in 1988 [19]. Realizing an FEL operation at wavelength shorter than 1000 Å is more difficult because the electron beam requirements are more demanding, and perhaps more importantly, because high reflectivity mirrors required for optical cavity are currently not available. The use of mirrors can be avoided if FELs are run in the amplifier mode. As the input radiation, if available at all, is usually quite weak, in the short wavelength region, the gain of the FEL in the amplifier mode must necessarily be very high. In the case of extreme high gain (one million or larger), the FEL can amplify the initial noise signal(the undulator radiation) to intense coherent radiation [20]. Although operation in this so-called self-amplified spontaneous emission(SASE) regime requires neither mirrors nor coherent input signals, the requirements on the electron beam qualities and the undulator construction is very demanding. Despite these difficulties, several laboratories are pursing short wavelength FELs [21], [22], [23], [24] because of the potentially high scientific pay-off [25].

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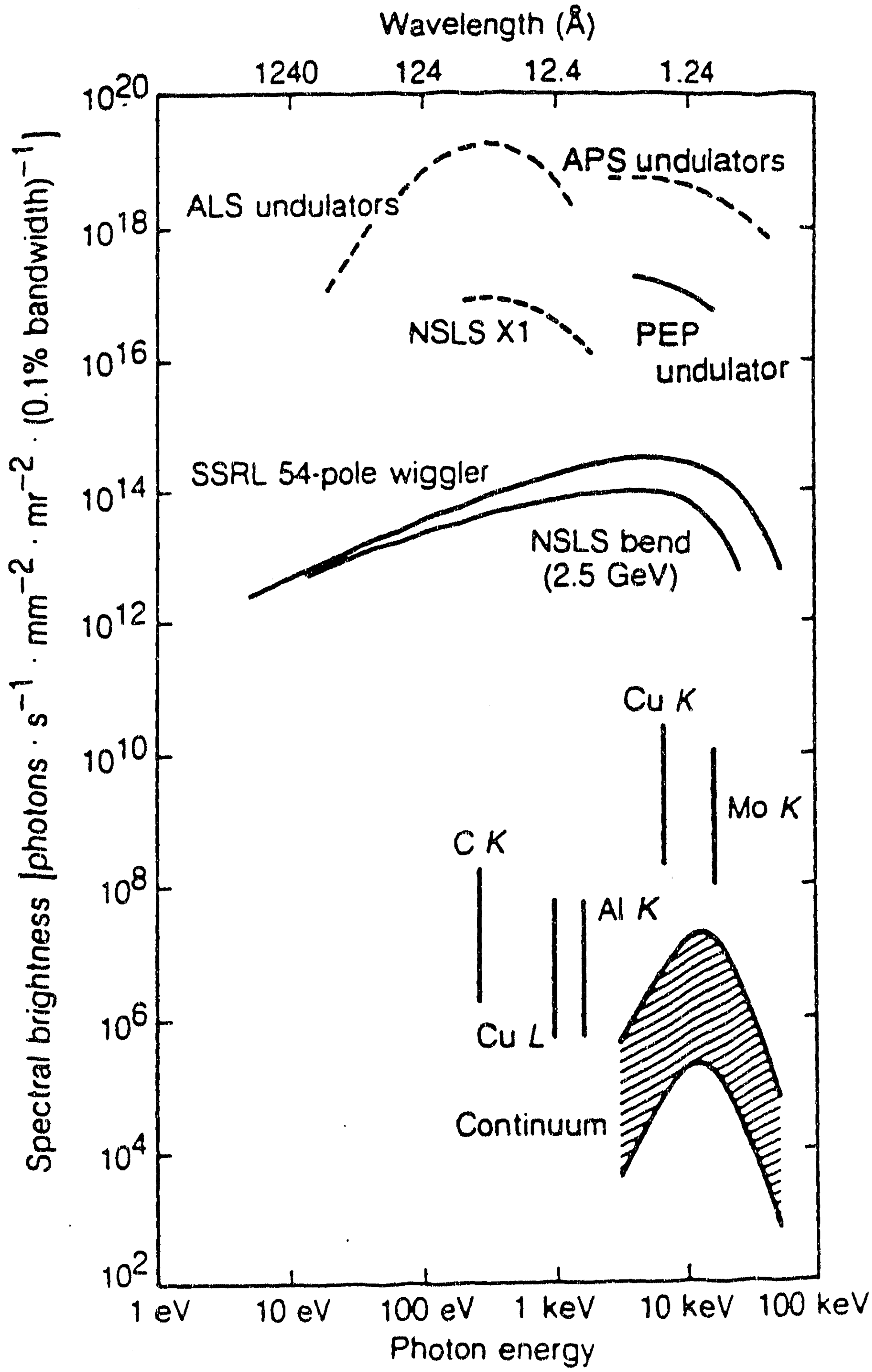
Figures

1. Average spectral brightness within a 0.1% bandwidths, as a function of photon energy, for a variety of synchrotron radiation sources.

2. Performance of FELs compared to other sources in different wavelength regions.



Wavelength (Å)
1240
124
12.4
1.24
10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
APS undulators
ALS undulators
NSLS X1
PEP undulator
SSRL 54-pole wiggler
NSLS bend (2.5 GeV)
Cu K
Mo K
C K
Al K
Cu L
Continuum
Spectral brightness [photons · s^{-1} · mm^{-2} · mr^{-2} · (0.1% bandwidth)$^{-1}$]
1 eV
10 eV
100 eV
1 keV
10 keV
100 keV
Photon energy

Figure 1

FELs May Provide Tunable, Coherent Radiation in the IR and UV Spectral Regions

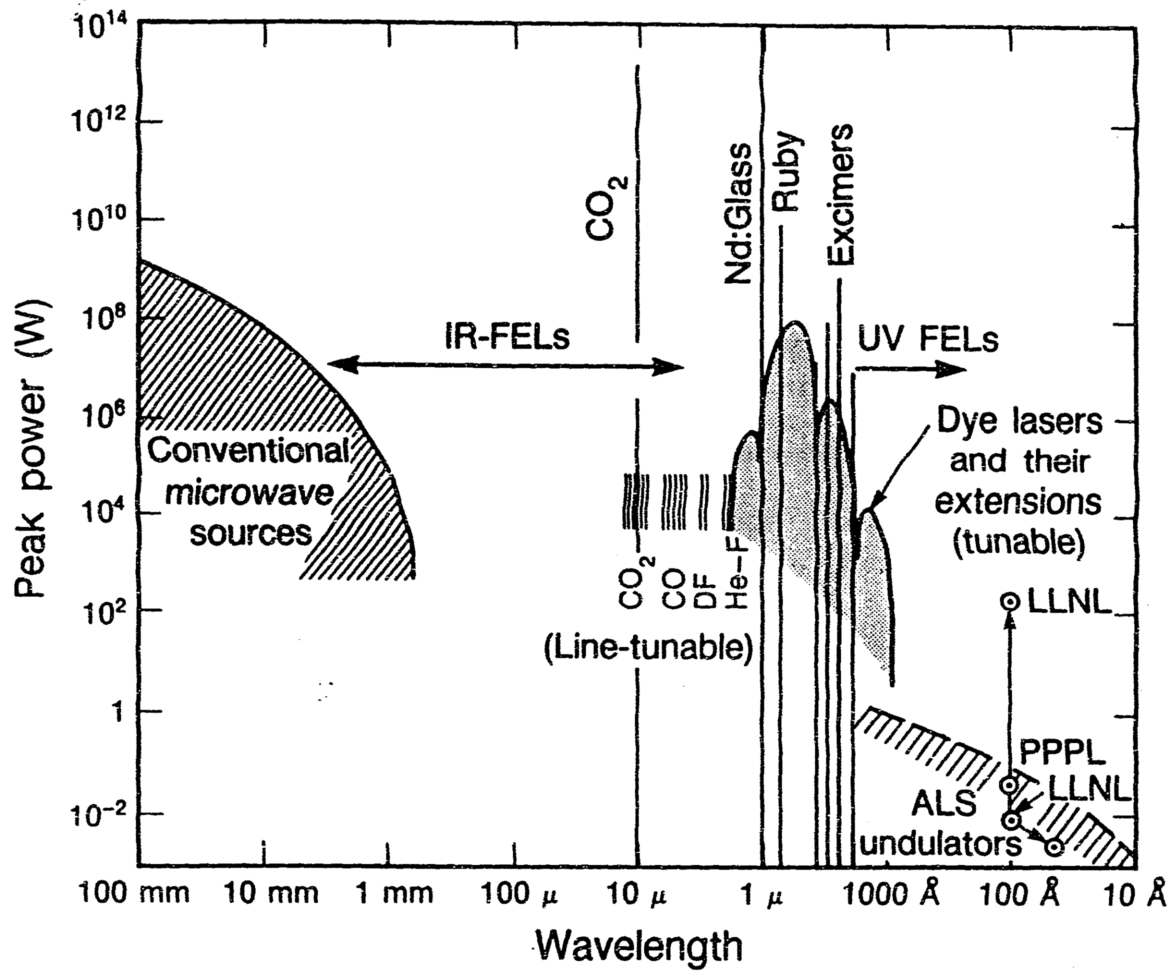


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Figure 2